**A Comprehensive Risk Evaluation Model for Occupational Safety in the Food Industry: Integration of HIRARC, FMEA, Fuzzy AHP, and FTA**

Aisyah Leilani Salsabilah1,a), Tyas Yuli Rosiani2,b), Annisa Kesy Garside3,c)

1,2,3Department of Industrial Engineering, University of Muhammadiyah Malang, Malang, Indonesia

a aisyahleilani@webmail.umm.ac.id

b)Corresponding author: [tyasyulirosiani@umm.ac.id](mailto:tyasyulirosiani@umm.ac.id)

c)  [annisa@umm.ac.id](mailto:baiqfiryal@umm.ac.id)

**Abstract.** Occupational safety in the food industry is a critical aspect that requires a comprehensive risk analysis approach. This study examines occupational safety risks in the production process using an integrated approach combining HIRARC, FMEA, Fuzzy AHP, and FTA. The HIRARC method is used to identify and assess risks based on severity and likelihood parameters, while FMEA is used to determine priorities based on the combination of Severity, Occurrence, and Detection values. To reduce subjectivity in weighting, Fuzzy AHP is applied to produce a more accurate assessment of these three parameters. The results show that the three highest-priority risks, namely FM6, FM31, and FM1, were further analysed using Fault Tree Analysis (FTA) to identify the root causes of workplace accidents in a logical and systematic manner. The integration of these four methods provides a comprehensive risk mapping and supports effective mitigative decision-making. The limitations of this study lie in the scope of data being restricted to internal observations. These findings are expected to serve as a foundation for developing a more effective and sustainable OSH management system in large-scale food industries.

**Keywords:** Occupational Safety; HIRARC; FMEA; Fuzzy AHP; FTA

# **INTRODUCTION**

In the increasingly competitive food manufacturing industry, companies continue to strive to improve productivity, product consistency, and operational efficiency [1]. However, achieving these goals will not be sustainable without ensuring a safe and healthy work environment for workers. Occupational Safety and Health (OSH) is a critical aspect of the industrial environment, particularly in the food manufacturing sector, which involves intensive interaction between humans, machinery, and chemicals [2, 3]. Failure to manage workplace risks not only impacts worker safety but also disrupts operational continuity and tarnishes the company’s reputation. In large-scale ready-to-eat food industries, the massive and continuous production processes result in more complex and significant workplace risks [4]. Therefore, systematic risk identification and control are necessary to minimize potential hazards and support the continuity of the production system [5]. In this context, accurate and data-driven occupational safety risk analysis is a critical foundation for making informed and prioritized decisions [6].

Previous studies have examined the application of occupational safety risk analysis methods in manufacturing environments [7, 8]. However, most of these approaches tend to be limited to certain stages of the production process or use only a single risk evaluation method. The main challenge that remains is how to conduct a comprehensive and systematic risk assessment across the entire production process chain One widely used method is HIRARC, which provides a systematic framework for risk identification and mitigation [9]. In recent studies, HIRARC is often combined with other methods to produce more accurate and multidimensional analyses [10], such as in the research conducted by Maia, et al. [11] which combines HIRARC with Fuzzy AHP to assess risk priorities, and the study by Choi [12] which combines it with FTA to identify the root causes of workplace accidents hierarchically. On the other hand, FMEA is also used for uncertainty-based risk assessment [13]. The combination of these methods has proven to enhance effectiveness in identifying, measuring, and controlling risks in a structured and data-driven manner. However, challenges remain regarding the subjectivity of assessments and the complexity of cause-and-effect relationships, necessitating an approach that can integrate the strengths of each method to produce more objective and accurate decision-making.

Although several methods have been integrated in previous studies, these approaches are still limited in terms of objectivity of weighting and visualization of cause-and-effect relationships. To address this, this study developed an integrated framework that combines risk identification using HIRARC, failure prioritization using FMEA, parameter weighting using Fuzzy AHP, and root cause analysis using Fault Tree Analysis (FTA). This framework encompasses hazard identification, structured evaluation of severity, likelihood, and risk detection, as well as logical analysis of the primary causes of workplace accidents. The objective of this study is to provide a more comprehensive risk evaluation approach to support effective and sustainable mitigation decision-making in the food manufacturing industry.

# **METHODS**

# **Proposed Framework**

This study proposes an integrated risk evaluation framework that includes four main stages: initial risk identification and assessment using HIRARC, failure mode analysis using FMEA, risk weighting using Fuzzy AHP, and root cause analysis using FTA. Figure 1 presents a systematic flow of the risk evaluation stages applied in this study.

**FIGURE 1.** Integrated Framework of Occupational Safety Risk Evaluation

**Hazard Identification and Initial Risk Assessment Using HIRARC**

The initial stage begins with the implementation of Hazard Identification, Risk Assessment, and Risk Control (HIRARC), which consists of three steps: hazard identification, risk assessment, and risk control [14]. Risk levels are classified into four categories: low, medium, high, and extreme [9], based on the combination of Severity (S) and Likelihood (L) calculated using Equation (1):

(1)

Where R = risk matrix score, S = severity, and L = likelihood of occurrence. R values are mapped into four categories: low (1–4), medium (5–9), high (10–19), and extreme (>20). These categories form the basis for targeted control priorities and mitigation strategies.

**Failure Mode and Effect Analysis Using FMEA**

The next step in this framework is risk assessment using the Failure Mode and Effects Analysis (FMEA) method. Each failure mode is analyzed based on three main parameters: Severity (S), which is the severity of the impact; Occurrence (O), which is the likelihood of failure; and Detection (D), which is the ability to detect failure before it has an impact [15]. The values of these three parameters are multiplied to produce the Risk Priority Number (RPN) as shown in Equation (2):

(2)

The RPN results are used to prioritize corrective actions, with higher values indicating greater urgency in implementing mitigation measures. This approach ensures that each failure mode is systematically identified, quantitatively assessed, and ranked based on its critical impact on safety and process performance.

**Risk Weight Determination Using Fuzzy AHP**

The next step is to apply Fuzzy AHP to determine the relative weights of the three main risk parameters, namely Severity (S), Occurrence (O), and Detection (D), with the aim of reducing uncertainty and subjectivity in expert assessment [16]. The evaluation is carried out using triangular fuzzy numbers to accommodate variations in assessment. The final risk value is calculated using Equation (3):

(3)

Where , , dan are the normalized weights of parameters S, O, and D, respectively. The weight calculation begins by determining the geometric mean of the fuzzy value fuzzy , which represents the comparison of criterion i to criterion j, as in Equation (4):

(4)

The value is multiplied by adjustment factor to produce the initial weight (Equation (5)):

(5)

Rata-rata bobot setiap elemen dihitung menggunakan Persamaan (6):

(6)

The average weight of each element is calculated using Equation (7):

(7)

These normalized weights are used in Equation (1) to calculate the ​, which then serves as the basis for determining risk priorities more accurately by considering the uncertainty in expert assessments.

**Deductive Accident Causation Analysis Using FTA**

The final stage in this framework is the application of Fault Tree Analysis (FTA) to identify and analyze the potential causes of a system failure (top event) [17]. FTA is structured in the form of an inverted tree diagram that starts from the top event at the top, then breaks down into various basic causes (basic events) using AND gate and OR gate logic symbols. AND gate indicates that all causes must occur simultaneously for the top event to occur, while OR gate indicates that the occurrence of one cause is sufficient to trigger the top event [18]. The analysis process is conducted deductively by breaking down the top event into sub-causes until reaching the basic events that cannot be further decomposed. This approach facilitates the visualization of logical relationships between causes, identifies critical points in the system, and prioritizes areas requiring corrective or preventive control measures.

# **RESULT AND DISCUSSION**

The evaluation using HIRARC successfully identified 35 occupational risks across all stages of production. The classification results showed 3 high risks, 17 medium risks, and 15 low risks, with the largest distribution in the medium category. High risks include poor lighting (H1), machine injuries (H6), and cuts from cutting tools (H31), which require immediate control measures. Medium risks are dominated by heat exposure, static work postures, and noise, while low risks are generally related to contamination and short-term exposure. The distribution of risks across the entire process underscores the need for a comprehensive mitigation approach, rather than a partial one. All risk identification, assessment, and control data are presented in Table 1, which demonstrates that a priority-based approach supports efficient resource allocation and strengthens the OSH management system sustainably.

**TABLE 1.** Integrated Occupational Hazard Identification, Risk Assessment, and Control Measures Based on HIRARC

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **No** | **Activity** | **Code** | **Potential Hazards** | **Hazard Risks** | **Matrix Score** | **Risk Rating** | **Risk Control** |
| 1 | Mixing process | H1 | Poor lighting | Fall | 12 | High | Add lighting to the mixing area. |
| H2 | Excessive noise from the mixer | Hearing impairment | 3 | Low | Use earplugs during the mixing process. |
| H3 | Exposure to splashes of hot jelly liquid | Burn | 9 | Medium | Use heat-resistant gloves. |
| H4 | Foreign objects entering the product | Product contamination | 1 | Low | Conduct routine inspections. |
| H5 | Lifting heavy raw materials | Muscle injury | 6 | Medium | Use lifting aids and proper posture. |
| 2 | Filling process | H6 | Finger caught in machine parts | Scratches | 12 | High | Ensure SOP compliance. |
| H7 | Exposure to hot jelly liquid | Burn | 9 | Medium | Use heat-resistant gloves and ensure volume control. |
| H8 | Standing too long | Muscle injury or fatigue | 6 | Medium | Provide ergonomics training. |
| H9 | Foreign objects in jelly | Product contamination | 1 | Low | Use complete PPE and maintain cleanliness. |
| H10 | Prolonged noise exposure from filling machine | Hearing impairment | 3 | Low | Use earplugs. |
| 3 | Pasteurization | H11 | High temperatures | Burn | 6 | Medium | Use PPE and ensure proper ventilation. |
| H12 | Hot liquid splashes | Burn | 9 | Medium | Use PPE and closed systems. |
| H13 | Residue in machine | Product contamination | 1 | Low | Inspect pipes and ensure ventilation. |
| H14 | Equipment damage | Fire | 5 | Medium | Conduct regular maintenance. |
| H15 | Temperature setting errors | Over/under pasteurization | 1 | Low | Check parameters regularly. |
| 4 | Cooling process | H16 | Water spillage | Slip and fall | 9 | Medium | Use anti-slip mats and clean spills promptly. |
| H17 | Unclean cooling water | Product contamination | 1 | Low | Use filtered and sterilized water. |
| H18 | Hot water exposure | Burn | 9 | Medium | Monitor and regulate temperature. |
| H19 | Overcooling | Texture changes | 1 | Low | Set time/temp per standard and monitor. |
| H20 | Pipe blockages | Temperature imbalance | 1 | Low | Clean filters and perform maintenance. |
| 5 | Drying process | H21 | Heat or dry air exposure | Dehydration/irritation | 2 | Low | Use PPE, hydrate, and ensure airflow. |
| H22 | Machine overheating | Fire | 5 | Medium | Monitor machine temperature. |
| H23 | High noise level from machine | Hearing impairment | 3 | Low | Use earplugs. |
| H24 | Damaged electrical cables | Electric shock | 5 | Medium | Inspect electrical systems regularly. |
| H25 | High humidity | Fungal growth/corrosion | 1 | Low | Control humidity and optimize drying. |
| 6 | Metal detection | H26 | Electromagnetic interference | Machine malfunction | 1 | Low | Minimize interference and maintain devices. |
| H27 | Calibration errors | Contamination | 1 | Low | Calibrate regularly. |
| H28 | Conveyor pinch points | Injuries | 9 | Medium | Install protective covers and enforce SOP. |
| H29 | Electromagnetic wave exposure | Radiation exposure | 4 | Medium | Maintain safe distance. |
| H30 | High temperature | Metal detection inaccuracy | 1 | Low | Monitor production area temperature. |
| 7 | Packing process | H31 | Injuries from cutters | Scratches | 10 | High | Use hand protection and provide safety training. |
| H32 | Lifting/bending for too long | Back pain and fatigue | 8 | Medium | Adjust workbench height and train ergonomics. |
| H33 | Foreign objects in packaging | Product contamination | 1 | Low | Use PPE and maintain hygiene. |
| H34 | Unstable packaging stacks | Being struck/fall | 8 | Medium | Limit stack height and use assistive tools. |
| H35 | Counting system errors | Incorrect quantity | 1 | Low | Use calibrated weighing/counting systems. |

Further risk evaluation was conducted using FMEA and Fuzzy AHP. FMEA showed that FM1, FM6, and FM31 had the highest RPN values, at 30 and 25, respectively. However, after weighting using Fuzzy AHP, the order of priority shifted. FM6 and FM31 ranked at the top with Fuzzy AHP RPN values of 3.316, followed by FM1 with a value of 3.223, as presented in Table 2. This comparison shows that the integration of Fuzzy AHP improves the accuracy of the assessment by considering uncertainty in the parameters [16]. The findings confirm that mechanical injuries and poor lighting are the most critical risks that need to be addressed immediately in the OSH system.

**TABLE 2.** Risk Priority Ranking Based on FMEA and Fuzzy AHP

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Code** | **FM** | **S** | **O** | **D** | **RPN** | **Rank** | **RPN Fuzzy AHP** | **Rank Fuzzy AHP** |
| H1 | FM1 | 2 | 5 | 3 | 30 | 1 | 3.223 | 3 |
| H2 | FM2 | 3 | 1 | 1 | 3 | 21 | 1.842 | 21 |
| H3 | FM3 | 2 | 4 | 2 | 16 | 6 | 2.644 | 9 |
| H4 | FM4 | 2 | 1 | 1 | 2 | 25 | 1.421 | 25 |
| H5 | FM5 | 2 | 3 | 4 | 24 | 4 | 2.836 | 4 |
| H6 | FM6 | 1 | 5 | 5 | 25 | 2 | 3.316 | 1 |
| H7 | FM7 | 2 | 4 | 2 | 16 | 6 | 2.644 | 9 |
| H8 | FM8 | 2 | 3 | 4 | 24 | 4 | 2.836 | 4 |
| H9 | FM9 | 2 | 1 | 1 | 2 | 25 | 1.421 | 25 |
| H10 | FM10 | 3 | 1 | 1 | 3 | 21 | 1.842 | 21 |
| H11 | FM11 | 2 | 4 | 2 | 16 | 6 | 2.644 | 9 |
| H12 | FM12 | 2 | 4 | 2 | 16 | 6 | 2.644 | 9 |
| H13 | FM13 | 2 | 1 | 1 | 2 | 25 | 1.421 | 25 |
| H14 | FM14 | 5 | 1 | 1 | 5 | 17 | 2.684 | 6 |
| H15 | FM15 | 1 | 5 | 1 | 5 | 17 | 2.288 | 16 |
| H16 | FM16 | 2 | 1 | 3 | 6 | 16 | 1.935 | 20 |
| H17 | FM17 | 2 | 1 | 1 | 2 | 25 | 1.421 | 25 |
| H18 | FM18 | 2 | 3 | 2 | 12 | 10 | 2.322 | 15 |
| H19 | FM19 | 1 | 1 | 1 | 1 | 32 | 1.000 | 32 |
| H20 | FM20 | 1 | 1 | 1 | 1 | 32 | 1.000 | 32 |
| H21 | FM21 | 2 | 2 | 2 | 8 | 13 | 2.000 | 18 |
| H22 | FM22 | 5 | 1 | 1 | 5 | 17 | 2.684 | 6 |
| H23 | FM23 | 3 | 1 | 1 | 3 | 21 | 1.842 | 21 |
| H24 | FM24 | 5 | 1 | 1 | 5 | 17 | 2.684 | 6 |
| H25 | FM25 | 1 | 2 | 1 | 2 | 25 | 1.322 | 31 |
| H26 | FM26 | 2 | 2 | 2 | 8 | 13 | 2.000 | 18 |
| H27 | FM27 | 2 | 1 | 1 | 2 | 25 | 1.421 | 25 |
| H28 | FM28 | 2 | 1 | 4 | 8 | 13 | 2.192 | 17 |
| H29 | FM29 | 3 | 1 | 1 | 3 | 21 | 1.842 | 21 |
| H30 | FM30 | 1 | 1 | 1 | 1 | 32 | 1.000 | 32 |
| H31 | FM31 | 1 | 5 | 5 | 25 | 2 | 3.316 | 1 |
| H32 | FM32 | 1 | 3 | 4 | 12 | 10 | 2.415 | 14 |
| H33 | FM33 | 2 | 1 | 1 | 2 | 25 | 1.421 | 25 |
| H34 | FM34 | 3 | 1 | 4 | 12 | 10 | 2.613 | 13 |
| H35 | FM35 | 1 | 1 | 1 | 1 | 32 | 1.000 | 32 |

After obtaining the three highest priority risks from the Fuzzy AHP results, the analysis was continued using Fault Tree Analysis (FTA) to logically trace the root causes of failure. Figure 1a shows that the top event was fingers or hands getting caught between machine parts, triggered by a combination of operator negligence, lack of machine guards, and inconsistent implementation of SOPs. Furthermore, Figure 1b illustrates injuries caused by the use of cutting tools such as knives or cutters as the top event. The main causes include insufficient safety training, failure to use hand protection, and high production pressure. This confirms that the risk from sharp tools is influenced by both technical and managerial aspects. Figure 1c shows the risk caused by inadequate lighting. The cause pathway indicates that poor lighting systems, lack of routine inspections, and failures in work area design are the primary triggers. These findings are consistent with previous research stating that low lighting increases the potential for workplace accidents.

Overall, the FTA results clarify the cause-and-effect relationship of priority risks and serve as the basis for developing systematic and preventive corrective actions, thereby supporting the strengthening of the OSH management system in the production area.

|  |  |
| --- | --- |
|  | |
| (a) | |
|  |  |
| (b) | (c) |

**FIGURE 2.** Fault Tree Analysis (FTA) for the Top Three Risk Events

**CONCLUSION**

This study successfully developed a comprehensive occupational safety risk assessment model through the integration of the HIRARC, FMEA, Fuzzy AHP, and FTA methods. This model was able to identify 35 occupational risks across all stages of production, with the majority classified as moderate risks. Through FMEA analysis and weighting using Fuzzy AHP, the three highest priority risks were identified: mechanical injuries caused by machinery (H6 and H31) and inadequate workplace lighting (H1). Further analysis using Fault Tree Analysis (FTA) revealed that the root causes of these three risks stem from technical failures, procedural weaknesses, and insufficient managerial oversight. The integration of these four methods yields a robust, data-driven approach for systematically identifying, prioritizing, and mitigating workplace hazards. Theoretically, this model contributes new insights into expanding multi-method approaches for occupational safety analysis, while practically, it is relevant for strengthening occupational safety and health (OSH) management systems, particularly in the food industry sector. The limitation of this study lies in the scope of the data, which is only from one company. Therefore, further research is recommended to test this model across industries to obtain external validation and refine mitigation strategies based on more diverse risk characteristics.

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